MURI: Impact of Oceanographic Variability on Acoustic Communications

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LONG-TERM GOALS

Couple together analytical and numerical modeling of oceanographic and surface wave processes, acoustic propagation modeling, statistical descriptions of the waveguide impulse response between multiple sources and receivers, and the design and performance characterization of underwater acoustic digital data communication systems in shallow water.

OBJECTIVES

Develop analytical/numerical models, validated with experimental data, that relate short-term oceanographic variability and source/receiver motion to fluctuations in the waveguide acoustic impulse response between multiple sources and receivers and ultimately to the capacities of these channels along with space-time coding and adaptive modulation/demodulation algorithms that approach these capacities.

APPROACH

The focus of this research is on how to incorporate an understanding of short-term variability in the oceanographic environment and source/receiver motion into the design and performance characterization of underwater acoustic, diversity-exploiting, digital data communication systems. The underlying physics must relate the impact of a fluctuating oceanographic environment and source/receiver motion to fluctuations in the waveguide acoustic impulse response between multiple sources and receivers and ultimately to the channel capacity and the design and performance characterization of underwater acoustic digital data communication systems in shallow water. Our approach consists of the following thrusts.

1. Modeling short-term variability in the oceanographic environment.

The long-term (beyond scales of minutes) evolution of the physical oceanographic environment (e.g. due to currents and long period internal waves) imparts slow changes to the waveguide acoustic propagation characteristics. In contrast, surface waves driven by local winds and distant storms exhibit dynamics on much shorter scales (seconds to tens of seconds) and directly impact short-term acoustic fluctuations. In addition, shorter-period internal waves, finestructure, and turbulence also will

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14. ABSTRACT
Couple together analytical and numerical modeling of oceanographic and surface wave processes, acoustic propagation modeling, statistical descriptions of the waveguide impulse response between multiple sources and receivers, and the design and performance characterization of underwater acoustic digital data communication systems in shallow water.

15. SUBJECT TERMS

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contribute to propagation variability. An important question is the relative impact each of these has on short-term acoustic fluctuations. Here we will couple models of the background time-evolving oceanographic environment with models of the surface wave dynamics to provide realistic sound speed fields along with their spatiotemporal correlation structure.

2. Transformation of environmental fluctuations and source/receiver motion into waveguide acoustic impulse response fluctuations between multiple sources and receivers.

Both ray-based (Sonar Simulation Toolset and Bellhop) and full-wave (Parabolic Equation) propagation modeling methods will be used to transform simulated sound speed fields, surface wave dynamics, and source/receiver motion directly into dynamic acoustic pressure fields. A Monte Carlo approach will be used to simulate realistic time-varying impulse responses between multiple sources and receivers. As an alternative, adjoint methods quantify the sensitivity of the channel impulse response to oceanographic (and geometric) variability. The linear approximation inherent in the sensitivity kernel may be valid for only a limited dynamic range of the environmental fluctuations corresponding to just a few seconds at the frequencies of interest but might provide useful insight into the mapping between environmental and acoustic fluctuations and subsequently to estimating the environmentally-dependent acoustic channel capacity.

3. Spatiotemporal statistical descriptions of waveguide impulse response fluctuations.

Statistical descriptions summarizing the spatiotemporal relatedness of waveguide impulse response fluctuations provide insight into the influence of environmental dynamics and can be used for system design and performance evaluation purposes. The scattering function provides a useful description of the channel in time delay and Doppler. In addition to estimating the scattering function from ensembles of realizations of fluctuating impulse responses (either from realistic simulations or at-sea observations), we also will use the sensitivity kernel for the impulse response combined with the dynamics and statistics of the environmental fluctuations to estimate the scattering function.

4. Channel capacity and the design and performance characterization of underwater acoustic, diversity-exploiting, digital data communication systems.

Channel capacity sets an upper bound on the information rate that can be transmitted through a given channel. The capacity of the highly dispersive and fluctuating ocean environment cannot be derived in closed form but only simulated or derived from measurements. In addition, realistic (constrained) capacity bounds will be derived that include practical implementation issues such as those imposed by phase-coherent constellations and realizable equalization schemes. Based on multiple source and receiver channel models developed from measured waveguide characteristics, we will assess the capacity of underwater acoustic channels and these will serve as goals for the design of space-time coding techniques and adaptive modulation/demodulation algorithms. An especially challenging problem in multipath-rich waveguides is the design of coherent communication schemes between moving platforms.

5. Benchmark simulations and validating experimental data.

A set of benchmark simulation cases will be defined for use in exploring transmitter/receiver design and performance characterization in the deployment of diversity-exploiting digital data telemetry systems (point-to-point and networked). Both fixed-fixed (stationary) and moving source and/or receiver scenarios will be considered across bands of frequencies in the range 1-50 kHz. Multiple

source and receiver cases (MIMO) will be of particular interest. Validating experimental data will be obtained during the ONR acoustic communications experiment in summer 2008 and other follow-on experiments to be scheduled in the future.

To address the issue of underwater acoustic digital data communication in a fluctuating environment, we have brought together a multidisciplinary research team consisting of oceanographers, ocean acousticians, and signal processors. Team members consist of faculty and researchers from four universities and unfunded collaborators from private industry and a navy laboratory:

- University of California, San Diego (UCSD) - W.S. Hodgkiss, W.A. Kuperman, H.C. Song, B.D. Cornuelle, and J.G. Proakis
- University of Washington (UW) - D. Rouseff and R. Goddard
- University of Delaware (UDel) - M. Badiey and J. Kirby
- Arizona State University (ASU) - T. Duman
- Heat, Light, and Sound (HLS) - M. Porter, P. Hursky, and M. Siderius (Portland State University)
- SPAWAR Systems Center – San Diego (SSC-SD) – V.K. McDonald and M. Stevenson

WORK COMPLETED

A shallow water acoustic communications experiment (KAM08) was conducted early summer 2008 off the western side of Kauai, Hawaii. Both fixed and towed source transmissions were carried out to multiple receiving arrays over ranges of 1-8 km. Substantial environmental data was collected including water column sound speed structure (CTDs and thermistor strings), water column current structure (ADCP), sea surface directional wave field (waverider buoy), and local wind speed and direction. Analysis of KAM08 data this past year has focused on the fixed source transmissions.

Publications related to this MURI include [1-11].

RESULTS

One area of analysis has been investigating the impact of daily variations of sound speed structure and source/receiver depth on shallow water acoustic communications [11]. Data collected during the Kauai Acomms MURI 2008 (KAM08) Experiment over a 35 hour period have shown how placement of the acoustic source and receiving hydrophones can capitalize on the acoustic propagation characteristics of the ~100 m deep waveguide. Vertical arrays of acoustic sources and receiving hydrophones separated by 4 km facilitated investigating the influence of source/receiver depth and oceanographic conditions.

The KAM08 Experiment was conducted in shallow water west of Kauai, Hawaii, in an area of substantial daily oceanographic variability. Specifically, the water column temperature structure (and, consequently, sound speed) varies from stratified to well-mixed as shown in Fig 1a. Also indicated are the source depths and apertures of the deep and more shallow subarrays of receiving hydrophones (6 elements each) located 4 km from the sources.

The propagation characteristics of an acoustic source in a waveguide depend on the depth of the source, water column sound speed structure, and seafloor geoacoustic properties. In a stratified water column with warmer shallow water overlying cooler deeper water, the transmissions from a deep source refract downward, interact with the seafloor, and couple well to the deep subarray of receiving hydrophones. This then results in a high output Signal-to-Noise-Ratio (SNR) from the communication receiver as shown in Figure 1b. At the same time, the more shallow subarray of receiving hydrophones is somewhat shielded from the deeper source and this results in a lower receiver output SNR as shown in Figure 1c. Of note in the experimental results are those from the mid-water depth source towards the end of the 35 hour data record. Here the sound speed structure stratification and subarray locations lead to performance similar to that observed with the deep source while in most other instances (except at the beginning of the data record when the water column also was stratified) the performance is more similar to that observed with the shallow source.

Another aspect of this analysis is quantifying the change in performance as array elements are added to the receiver. The data results in Fig. 2 are from the period of significant water column stratification discussed above (towards the end of the 35 hour period at 06:30 UTC in Fig.1a). As shown in Fig. 2a for the deep source, the cumulative increase in Signal-to-Noise-Ratio (SNR) at the output of the communications receiver increases quickly but then levels off sharply with the addition of hydrophones starting at the bottom of the array. Although performing less-well initially, the source in the middle of the water column is better positioned to couple energy into the upper elements of the receiving array and more total energy when all array elements are considered. The shallow source performs the least-well of the three since it poorly couples energy into the waveguide. In Fig. 2b, receiving elements are accumulated starting with the top of the array. Here, all three sources initially exhibit similar performance but the middle water column source increases rapidly with the addition of array elements. Interestingly enough, the deep and shallow sources exhibit equivalent and relatively modest increases in performance for the entire upper half of the receiving array. Only when the deeper array elements intercept energy focused near the seafloor from the deeper source does the performance of the two begin to differ. The performance of the deeper source then increases rapidly with the addition of array elements from the lower half of the receiving array.

IMPACT / APPLICATIONS

Acoustic data communications is of broad interest for the retrieval of environmental data from in situ sensors, the exchange of data and control information between AUVs (autonomous undersea vehicles) and other off-board/distributed sensing systems and relay nodes (e.g. surface buoys), and submarine communications.

RELATED PROJECTS

In addition to other ONR Code 321OA and Code 321US projects investigating various aspects of acoustic data communications from both an ocean acoustics and signal processing perspective, a second MURI also is focused on acoustic communications (J. Preisig, “Underwater Acoustic Propagation and Communications: A Coupled Research Program”).

PUBLICATIONS

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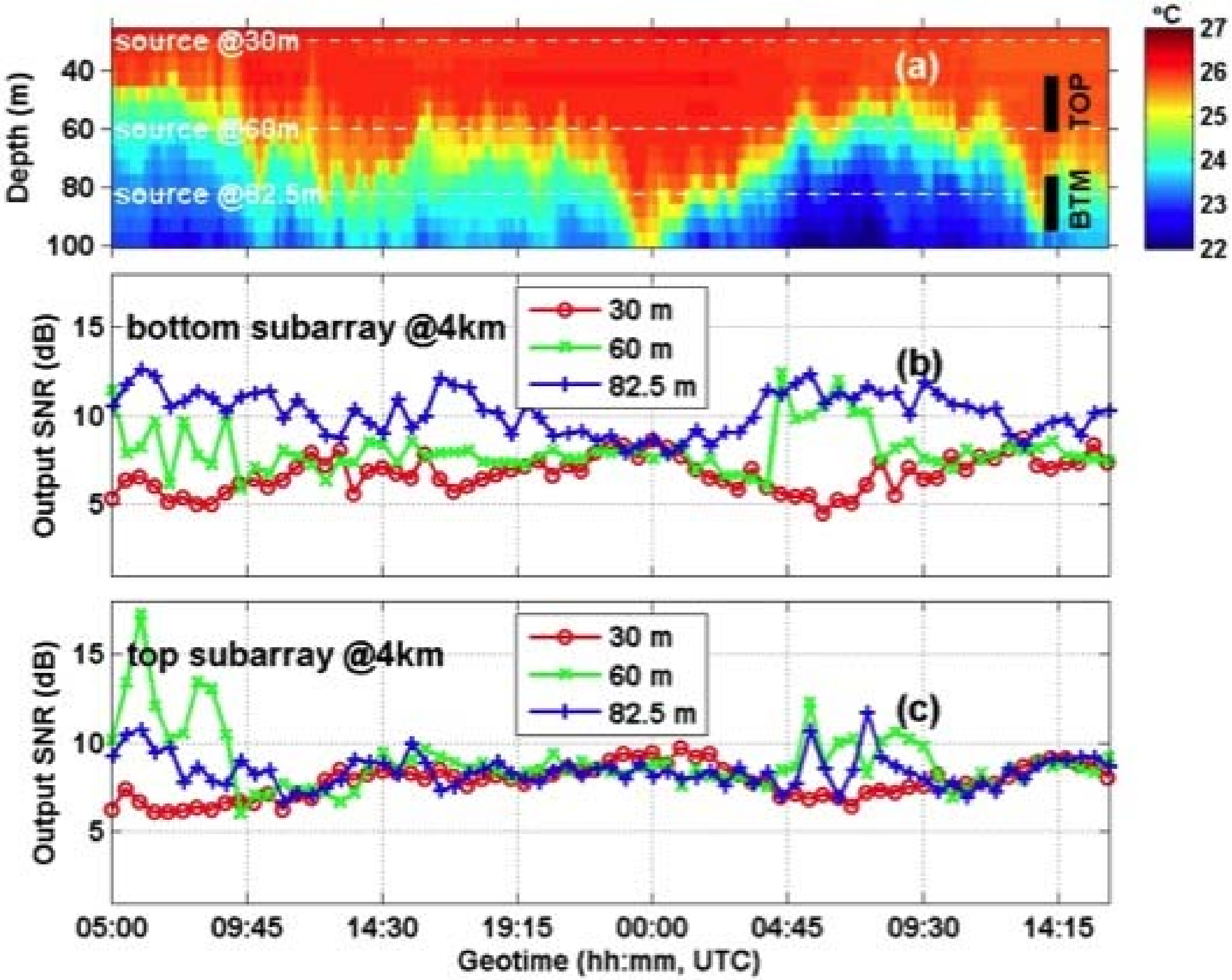
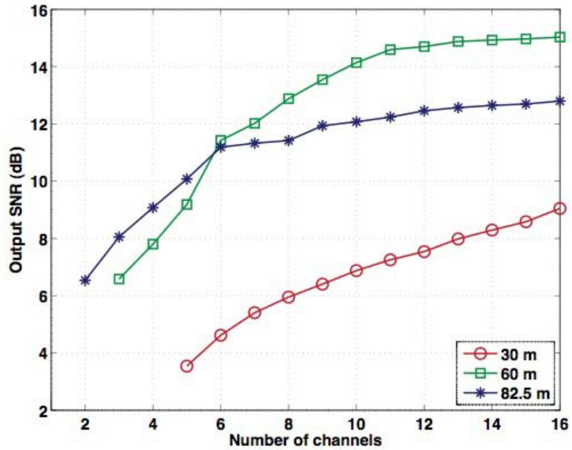


Figure 1. Acoustic communications in shallow water west of Kauai. (a) Water column temperature structure (and, consequently, sound speed). (b) Communications performance for deep subarray of hydrophones. (c) Communications performance for a shallow subarray of hydrophones.



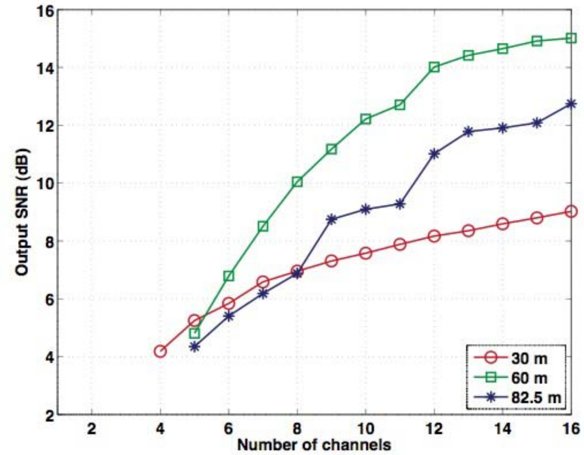


Figure 2. Acoustic communications in shallow water west of Kauai with sources (30 m, 60 m, and 82.5 m) separated 4 km from a large-aperture vertical receiving array. (a) Communications performance as receiving array elements are accumulated starting from the bottom of the array. (b) Communications performance as receiving array elements are accumulated starting from the top of the array.